BOBCAT FIRE: FINAL REPORT

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Bobcat Fire: Final Report

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1. INTRODUCTION

The Bobcat Fire burned over 4200 ha in the Big Thompson watershed 19 km northwest of Loveland, CO in June 2000. Most of the burned area was in the mid-elevation (2000-3230 m) zone where the dominant vegetation was ponderosa pine, interspersed with small stands of lodgepole pine and Douglas fir. Approximately 45% of the area was burned at high severity. The burned area is underlain by granitic and metamorphic rocks, and soils are generally gravelly sandy loams.

Following the fire, several studies were initiated to monitor the effects of burning on soil and water resources. The overall objectives of this work were to: 1) assess the presence and persistence of fire-induced soil water repellency, 2) measure runoff and erosion from small plots with a rainfall simulator, 3) measure sediment yields at the hillslope scale, 4) evaluate the effectiveness of Burned Area Emergency Rehabilitation (BAER) treatments, and 5) characterize the streamflow and sediment yield response from two burned watersheds. The research conducted primarily at the Bobcat Fire resulted in the completion of three M.S. theses (Huffman, 2001; Kunze, 2003; Wagenbrenner, 2003) and one Ph.D. dissertation (Benavides-Solorio, 2003). This final report summarizes the work done on the Bobcat Fire by Colorado State University under USFS grant 06-CS-11021000-038 (CSU 5-3 8868).

2. RESULTS

2.1. Controls on Post-Fire Soil Water Repellency

Fire-induced soil water repellency is thought to be the cause of increased runoff from burned watersheds in the Colorado Front Range, but data on the presence and persistence of water repellency are lacking. To address this lack of knowledge, soil water repellency was measured at 36 burned sites within the Bobcat Fire--including sites burned at high, moderate, and low severity--and at 9 unburned sites just outside the fire perimeter. Soil water repellency measurements were made during the month following burning and at 3 and 12 months following the fire.

Results from the Bobcat fire and four other fires in the Colorado Front Range indicate that sites burned at high and moderate severity were often strongly water-repellent at 0, 3, and 6 cm depth, whereas unburned sites and sites burned at low severity were typically water-repellent only at the soil surface (Huffman et al., 2001). Water-repellency strengthened with increasing burn severity, but statistically significant differences were difficult to determine due to the high spatial variability (Huffman et al., 2001). No significant differences in soil water repellency were found between sites with ponderosa pine and sites dominated by lodgepole pine.

Burn severity, percent sand, and percent soil moisture explained between 30 and 41% of the variability in soil water repellency. Soil water repellency increased with increasing percent sand and decreased with increasing soil moisture (Huffman et al., 2001).

The successive soil water repellency measurements made at the Bobcat Fire show that water repellency weakens after three months and is statistically non-detectable 12

months after burning (MacDonald and Huffman, 2004). As soils wet up they no longer are water repellent. At unburned sites soils became hydrophilic at about 10% soil moisture content, while the threshold for the change from hydrophobic to hydrophilic appears to increase with increasing burn severity. For sites burned at low severity the apparent soil moisture threshold is 13%, and no less than 26% for sites burned at high severity (MacDonald and Huffman, 2004). Although soil water repellency was statistically non-detectable 12 months after burning, sediment yields at the Bobcat Fire were higher in summer 2001 than in summer 2000 (Benavides-Solorio and MacDonald, 2001; Bevavides-Solorio and MacDonald, in press). The rapid decline in soil water repellency and the lack of any drop in sediment production rates suggests that post-fire soil water repellency is not the primary control on post-fire erosion rates.

2.2. Post-Fire Runoff and Sediment Yields Over Time from Small Plots

The high spatial variability and unpredictability of summer rainstorms can make it difficult to compare sediment production rates between sites and to rigorously compare the effects of different site factors. Rainfall simulations allow more controlled comparisons between sites, and they also facilitate the measurement of runoff rates as well as sediment yields. Simulated rainfalls of 80 mm h^{-1} were applied on 16 plots at the Bobcat Fire and 10 plots at two nearby prescribed fires in summer 2000. Measurements at the Bobcat Fire were repeated in 2001 and 2002 to assess the changes in runoff and sediment production rates over time.

For the rainfall simulations on the Bobcat Fire in summer 2000, 66% of the applied rainfall was converted to runoff for the plots that burned at high severity. For the

plots that burned at moderate severity, only 58% of the rainfall was converted into runoff, and this difference was significant at $p<0.05$ (Benavides-Solorio and MacDonald, 2001). The proportion of runoff from unburned plots and plots burned at low severity were not significantly different from the plots that burned at moderate severity (Benavides-Solorio and MacDonald, 2001). Univariate regression analyses of the simulation data from all three fires indicates that the proportion of runoff increases with increasing soil water repellency ($R^2 = 0.38$). The relationship between soil water repellency and percent runoff was much stronger for the plots that burned at high severity ($R^2 = 0.81$), while the proportion of runoff significantly declined with increasing soil moisture ($R^2 = 0.71$) (Benavides-Solorio and MacDonald, 2001).

Mean sediment yields from the sites burned at high severity were 5 times greater than the mean sediment yields from plots burned at moderate severity, and 10-26 times greater than the sediment yields from unburned plots and plots burned at low severity. The mean sediment yields from the unburned plots and the plots burned at low severity were significantly different from the plots burned at high severity, but were not significantly different from in the case of the plots burned at moderate severity (Benavides-Solorio and MacDonald, 2001). The best predictor of plot-scale sediment yields was percent bare soil, as this explained 81% of the variability in sediment yields (Benavides-Solorio and MacDonald, 2001).

For plots burned at high severity, the mean runoff ratio decreased from 66% in 2000 to 46% in 2001. In contrast, the mean sediment yields for these sites declined by only 4% from 2000 to 2001. The small decline in sediment yields may be explained by

the relatively small decrease in mean percent bare soil--from 89% in 2000 to 78% in 2001 (Benavides-Solorio, 2003).

In 2002 the mean rainfall/runoff ratio was 51%, and in 2003 the mean rainfall/runoff ratio was 55% (Benavides-Solorio et al., in preparation). These data show that runoff rates declined significantly in the first year after burning, but changed relatively little after that. In contrast, the mean sediment yield in 2002 was only 40% of the mean value measured in 2000, and by 2003 the mean sediment yields had dropped to just 17% of the mean value from summer 2000 (Benavides-Solorio et al., in preparation). The decrease in sediment yields was strongly correlated to the decline in percent bare soil from 53% in 2002 to 22% in 2003.

2.3. Hillslope-Scale Sediment Yields and Predictive Models

Following the Bobcat Fire, 16 sediment fences were installed to measure hillslope-scale sediment yields, and 32 sediment fences were installed on five other wild and prescribed fires in the Colorado Front Range. Within each fire precipitation was measured with a tipping bucket rain gage. The site-specific variables measured for each sediment fence included contributing area, aspect, percent ground cover, soil texture, and soil water repellency. The mean contributing area for these study sites was 1,250 m^2.

Sediment yields from high severity fires ranged from 2-10 Mg ha^{-1} yr^{-1}. Mean sediment yields from sites burned at moderate and low severity were only 0.2 and 0.05 Mg ha^{-1} yr^{-1}, respectively (Benavides-Solorio and MacDonald, in press). Over 90% of the sediment was generated by summer thunderstorms rather than winter snowmelt. Univariate regressions indicated that percent bare soil, hillslope topography, soil water-

repellency, and rainfall erosivity were each significantly correlated with annual sediment yields (Benavides-Solorio and MacDonald, in press).

A series of multivariate models were developed to predict post-fire sediment yields. The best model included the independent variables of percent bare soil, rainfall erosivity, fire severity, soil water repellency, and soil texture. This empirical model explained 77% of the variability in measured sediment yields. A simplified model using only percent bare soil and rainfall erosivity explained 65% of the variability in sediment yields (Benavides-Solorio and MacDonald, in press). The small decline in R^2 from the 5-parameter model to the 2-parameter model suggests that percent bare soil and rainfall erosivity are the dominant controls on post-fire sediment yields in the Colorado Front Range, and that a fairly simple model can predict post-fire sediment yields almost as accurately as a more complex model (Benavides-Solorio and MacDonald, in press).

In the case of the Bobcat fire, sediment production rates approached background levels in summer 2003, when the percent bare soil generally dropped below 35%. The one exception is at Green Ridge, where vegetative regrowth has been much slower, presumably as a result of the coarser-textured granitic soils. The largest annual sediment production rate measured from any site in any fire was 34 Mg ha^{-1} from one plot at Green Ridge in summer 2003, and this was due to 42 and 33 mm of rainfall falling in less than three hours on consecutive days. We are continuing to monitor the Green Ridge sites because the sediment production rates are still elevated to pre-fire conditions. The longer-term monitoring of these sites is important because they indicate the variability in the post-fire recovery rates, the potential for post-fire runoff and erosion rates to remain

elevated for more than 2-3 years, and the importance of soil texture in controlling the rate of vegetative regrowth and the decline in post-fire sediment production rates.

2. 4. Evaluation of BAER Treatment Effectiveness

Sediment yields from 12 untreated hillslopes were compared with sediment yields from 22 treated hillslopes to assess the effectiveness of the three BAER treatments applied after the Bobcat fire (seeding, straw mulch, and contour-felled logs) (Wagenbrenner et al., in review). Sediment yields from these hillslopes were monitored from August 2000 to October 2003. The installation quality of contour-felled logs was measured at the Bobcat Fire and two other Colorado Front Range fires, as the quality of installation should affect the potential effectiveness of this treatment (Wagenbrenner et al., in review).

The largest storm over the entire monitoring period occurred on 16 August 2000 as the study plots were being established. This storm dropped 48 mm of rain in two hours, and this is estimated to have a recurrence interval of 5 to 10 years (Wagenbrenner et al., in review). This storm caused more erosion than any other storm during the study period, as 12 of the 16 sediment fences that were in place at this time were overtopped by sediment. This meant that most of the sediment yields for summer 2000 were largely a function of the capacity of the sediment fences. Given this caveat, the mean sediment yield for the control plots was at least 6.2 Mg ha^{-1}, and none of the treatments had significantly different sediment yields (Wagenbrenner et al., in review). However, none of the sediment fences on the mulched plots were overtopped, suggesting that mulching

may have reduced sediment yields from the large storm on 16 August (Wagenbrenner et al., in review).

Mean sediment yields from the control plots increased to 9.5 Mg ha^{-1} in 2001, and then declined rapidly to 1.2 Mg ha^{-1} in 2002 and 0.7 Mg ha^{-1} in 2003. The corresponding mean sediment yields for the mulched plots were 0.02 Mg ha^{-1} in 2001, 0.006 Mg ha^{-1} in 2002 and 0.0 Mg ha^{-1} in 2003. Only the mulched plots had significantly lower sediment yields than the untreated control plots (Wagenbrenner et al., in review). The mulched plots also had significantly more ground cover than the controls throughout the study period, indicating that increased vegetative regrowth compensated for the loss and decay of the straw mulch. Contour felling did not reduce significantly reduce hillslope-scale sediment yields relative to the controls. On average, 32% of the contour-felled logs failed, primarily due to improper installation (Wagenbrenner et al., in review). Neither aerial nor hand seeding had a detectable effect on the amount of vegetative regrowth, percent bare soil, or sediment yields (Wagenbrenner et al., in review).

2.5. Streamflow and Sediment Yield Response to Burning

Following the Bobcat Fire, two small watersheds were monitored to determine streamflow and sediment yield response to burning as well as the effectiveness of BAER treatments. Nearly 100% of each watershed was burned, with 52% and 66% being burned at high severity. BAER treatments were applied to 65% of the Bobcat Gulch catchment, and the treatments applied included aerial seeding, contour felling, mulching, and the placement of straw wattles. In contrast, only 24% of Jug Gulch was treated by

aerial seeding. Precipitation, streamflow, suspended sediment, and turbidity were measured at the outlet of each watershed.

Two months after the Bobcat Fire a convective storm with a maximum 30-minute intensity of 42 mm hr^{-1} generated an estimated peak flow of 3900 L sec^{-1} km^{-2} in Bobcat Gulch. The corresponding peak flow in Jug Gulch was less than 5 L sec^{-1} km^{-2}, and the data from several rain gages show that the much lower discharge in Jug Gulch was due to the spatial variability in rainfall rather than any differences in catchment characteristics or BAER treatments (Kunze, 2003).

In the second summer after the Bobcat fire (2001), storms with maximum 30-minute intensities of 23 and 32 mm hr^{-1} generated peak discharges of 1100 and 1700 L sec^{-1} km^{-2} in Bobcat and Jug Gulch, respectively (Kunze, 2003; Kunze and Stednick in press). A maximum 30-minute intensity of approximately 10 mm hr^{-1} was needed to initiate storm runoff and sediment yields. The maximum single-storm sediment yields were 370 kg ha^{-1} in Bobcat Gulch and 950 kg ha^{-1} in Jug Gulch. Overall, 90% of the total sediment yield in each watershed was generated by the one or two most intense storms, and these had recurrence intervals of two years or less (Kunze, 2003; Kunze and Stednick, in press).

The effectiveness of the BAER treatments was inconclusive due to watershed differences and the high spatial variability in the convective rainstorms that generated most of the runoff and sediment. Hydrologic recovery in the third year after burning (2002) could not be evaluated due to the lack of storm events.

3. CONCLUSIONS

As indicated by the attached references, there have been more studies on post-fire runoff and erosion at the Bobcat fire than any other wildfire in the U.S. The work is particularly unique because measurements began immediately after the fire was controlled, and have been continuing until runoff and sediment production rates approach background levels. The work initiated on the Bobcat fire has triggered a series of other studies, and funds from the Joint Fire Science Program are being used to continue the measurements at Green Ridge. The lessons from the Bobcat fire helped guide the BAER treatments applied on the much larger Hayman fire in summer 2002, and the data gathered to date has greatly contributed to our understanding of post-fire runoff and erosion processes in the Colorado Front Range. In closing, we are very grateful to Carl Chambers and the staff of the Arapaho-Roosevelt National Forest for their assistance and support of this work.

4. LITERATURE CITED

Benavides-Solorio, Juan de Dios, 2003. Post-fire runoff and erosion at the plot and hillslope scale, Colorado Front Range. Ph.D. dissertation, Colorado State University, Fort Collins, CO, 218 p.

Benavides-Solorio, J., and MacDonald, L.H., 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. *Hydrological Processes* 15: 2931-2952.

Benavides-Solorio, J., and MacDonald, L.H., in press. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. *International Journal of Wildland Fire*.

Benavides-Solorio, J., MacDonald, L.H.,and Hughes, D.J., in preparation. Use of a rainfall simulator to evaluate post-fire runoff and erosion rates over time, Colorado Front Range.

Huffman, E.L., MacDonald, L.H., and Stednick, J.D., 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. *Hydrological Processes* 15: 2877-2892.

Huffman, E.L., 2001. Fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 186 p.

Kunze, M.D., 2003. Streamflow and sediment yield following the 2000 Bobcat Fire, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 133 p.

Kunze, M.D., and J.D. Stednick, in press. Streamflow and suspended sediment yields following the 2000 Bobcat fire, Colorado. *Hydrological Processes* 19.

MacDonald, L.H., and Huffman, E.L., 2004. Post-fire soil water repellency: Persistence and soil moisture thresholds. *Soil Science Society of America Journal* 68: 1729-1734.

Wagenbrenner, J.W., 2003. Effectiveness of burned area emergency rehabilitation treatments, Colorado Front Range. M.S. thesis, Colorado State University, Fort Collins, CO, 193 p.

Wagenbrenner, J.W., MacDonald, L.H., and Rough, D., *in review*. Effectiveness of three post-fire rehabilitation treatments in the Colorado Front Range. Submitted to *Hydrological Processes*.

Post-fire Runoff and Erosion in the Colorado Front Range: Processes and Rehabilitation

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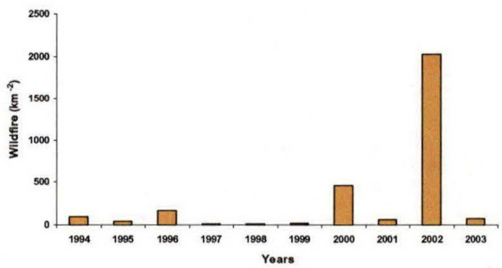
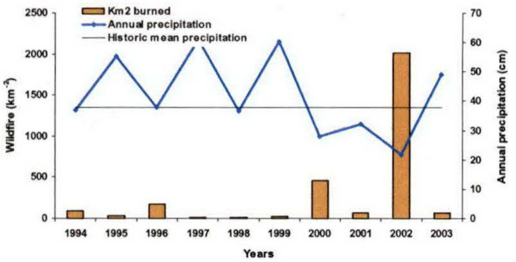
Area Burned in USFS Region 2, 1994-2003



Area Burned and Precipitation, 1994-2003



Erosion after a 100-year storm on the 1996 Buffalo Creek fire southwest of Denver, Colorado

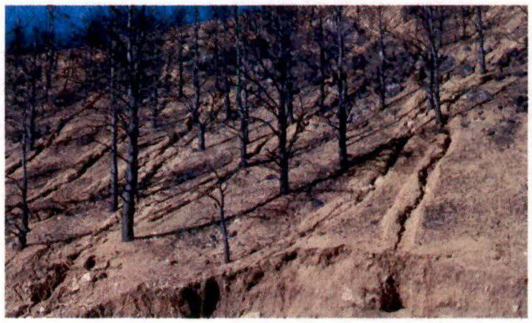


Photo by John Moody, USGS

High flows from a storm with a 30-minute rainfall intensity of 19 mm/h one year after the Buffalo Creek fire.

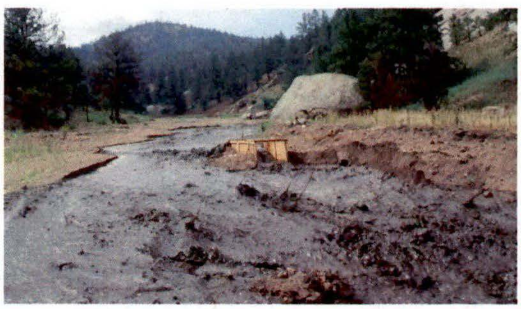


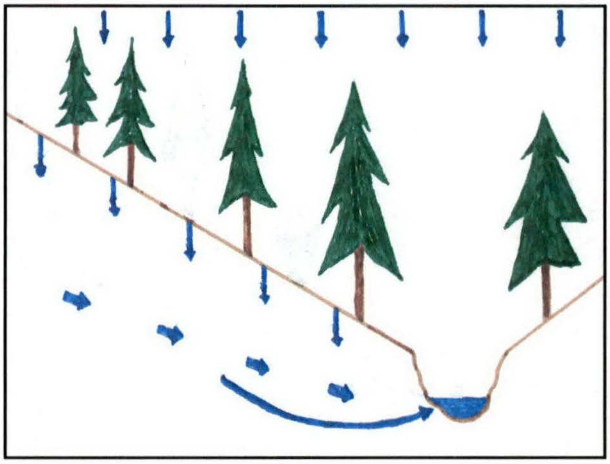
Photo by John Moody, USGS

Channel incision from a 20 mm/hr rain event after the Cerro Grande Fire near Los Alamos, NM.

Photo by John Moody, USGS

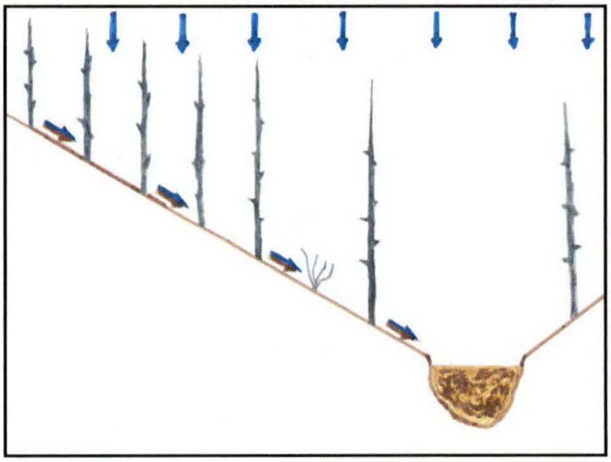
Deposition of coarse sand and gravel after the Cerro Grande fire in northern New Mexico.

Photo by John Moody, USGS



Hydrology of Unburned Forests

- Coarse-textured soils (>60% sand);
- High infiltration rates (typically $\geq$ 3 cm hr^{-1});
- Generally good ground cover (usually $\geq$ 80%);
- Storm runoff generated primarily by subsurface stormflow;
- Low peak flows from all but highest-magnitude storm events;
- Very low mean erosion rates (<0.1 t ha^{-1} yr^{-1});
- Clean, high quality water.

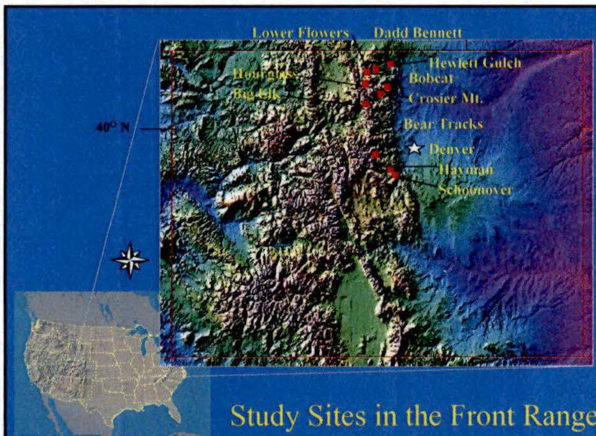


Post-fire Hydrology

- Possible water repellent layer in the soil;
- Loss of surface cover;
- Shift in runoff processes from sub-surface stormflow to infiltration-excess (Horton) overland flow;
- Large increases in peak flow and erosion rates;
- Downstream sedimentation;
- Degradation in water quality (turbidity, suspended sediment, nitrate, manganese, dissolved organic carbon) and aquatic habitat.

Objectives of Talk

1. Provide a quantitative understanding of how prescribed and wild fires affect runoff and erosion rates;
2. Evaluate the role of the different processes controlling post-fire runoff and erosion rates;
3. Discuss the effectiveness of different post-fire rehabilitation treatments, and use a process-based understanding to explain our results;
4. Identify key data gaps and limitations.



Study Sites in the Front Range

Collecting Data at Different Spatial Scales

- Point scale: soil water repellency;
- Small plot scale:
  - Runoff and sediment yields from rainfall simulations on 1 m^2 plots;
- Hillslope scale:
  - Sediment production from planar hillslopes and swales (zero-order catchments) using sediment fences;
  - Using paired-swale design to compare rehabilitation techniques against untreated controls;
- Small catchment scale:
  - Runoff, suspended sediment yields, water quality, and channel morphology.

Fortuitous Collection of Pre-fire Data

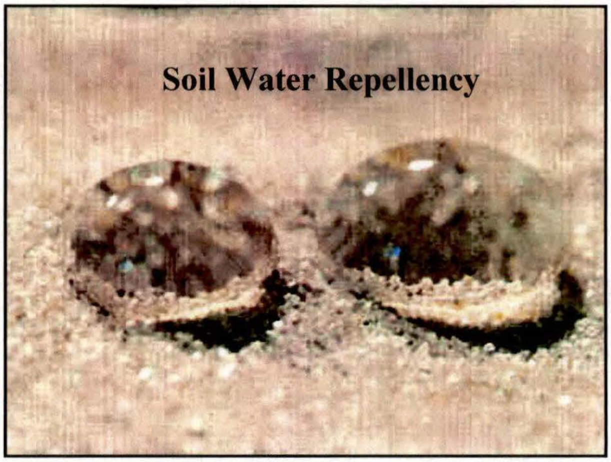
- Goal was to evaluate the effects of a proposed thinning project;
- Began monitoring percent cover, erosion rates, water quality, and channel morphology in mid-2001 on sites southwest of Denver;
- Majority of study sites burned in June 2002 Hayman fire, so have pre- and post-fire data at hillslope and small catchment scales.

Important Caveats

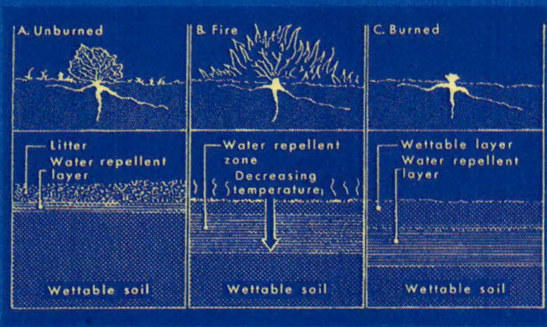
1. Data only from central and northern Colorado Front Range;
2. Only now being able to shift from comparisons between sites to documenting the complete sequence at single sites (i.e., from immediately after burning through hydrologic recovery);
3. Results depend in part on the magnitude of storm events over the monitoring period;
4. Uncertainty with respect to extrapolating our results and models over space and time.

Post-fire Effects Vary with Burn Severity

- Burn severity classified as high, moderate or low, depending on consumption of litter and soil organic matter;
- Severity is not equal to intensity, but often assumed to be closely correlated.



Fire-induced soil water repellency



(DeBano, 1981)

Methods

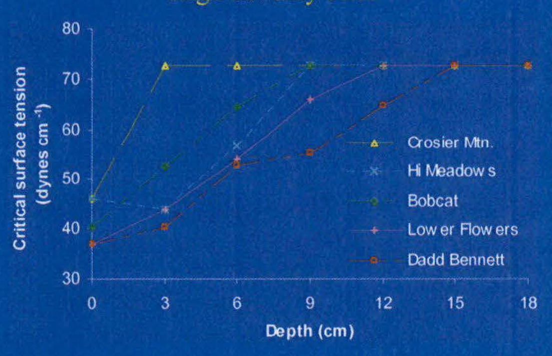
Water drop penetration time (WDPT):

- Apply drops at 3-cm depth increments beginning at mineral soil surface;
- Indefinite waiting time.

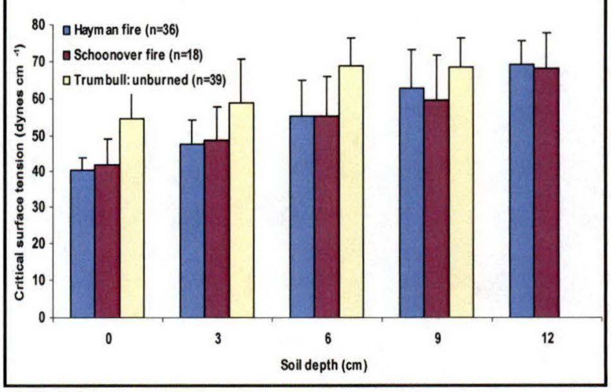
Critical surface tension test (CST):

- Apply 5 drops of de-ionized water;
- If pure water is not absorbed within 5 seconds, test solutions with progressively higher ethanol concentrations (increasing ethanol concentrations decrease surface tension);
- Critical surface tension (CST) is the tension of the first solution that is readily absorbed into the soil.

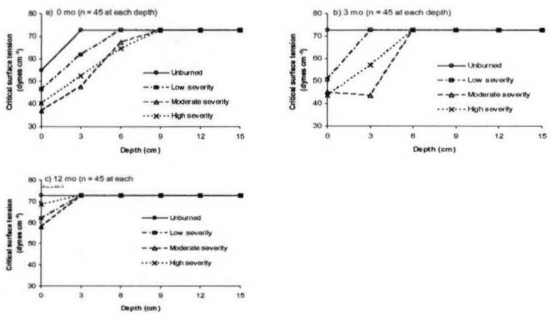
Critical Surface Tension by Depth: High Severity Sites



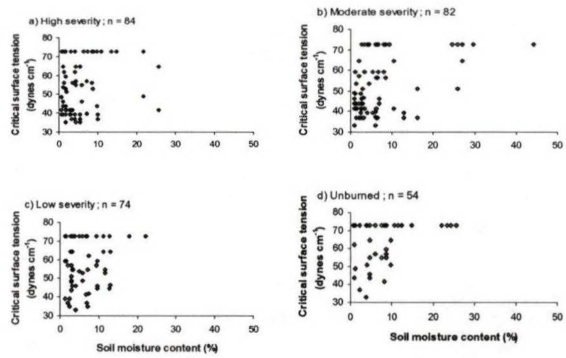
Mean Soil Water Repellency by Depth: Burned and Unburned Swales



Soil water repellency over time: Bobcat fire



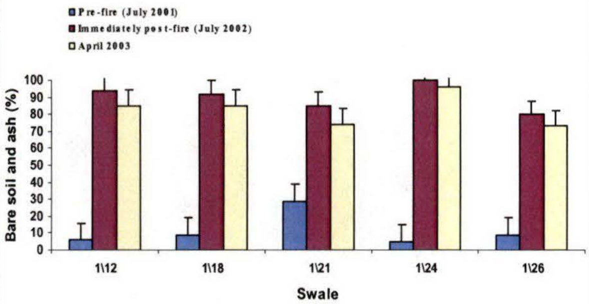
Effect of soil moisture on water repellency



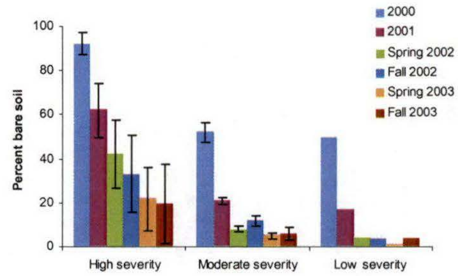
Conclusions: Soil Water Repellency

- Surface in unburned areas naturally water repellent;
- Fire-induced water repellency is relatively shallow (maximum of 9 cm);
- May be stronger in prescribed fires due to higher fuel loadings and slower rate of fire spread;
- Very high spatial variability;
- Relatively rapid recovery (≤ 2 years);
- Not present under wet conditions (12 to 30+ percent soil moisture), depending on fire severity;
- CST faster and more consistent than WDPT.

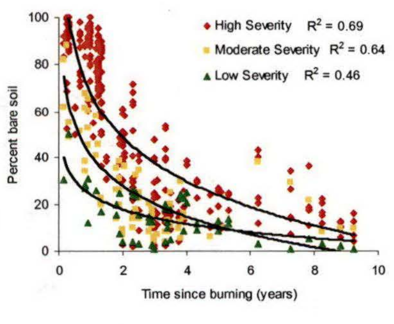
Percent bare soil over time: Hayman fire

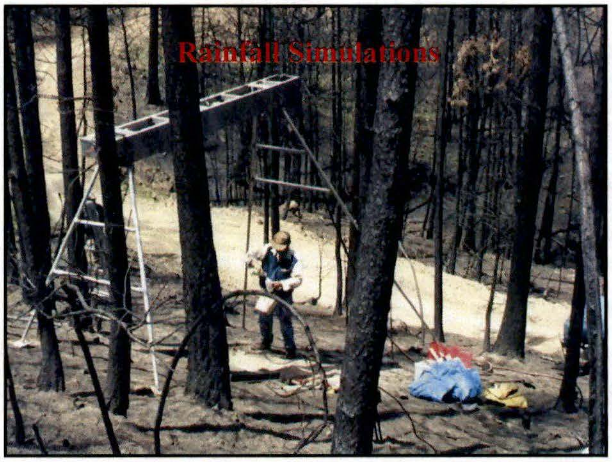


Percent bare soil in the Bobcat fire by fire severity and year



Percent Bare Soil Over Time, All Sites





Advantages of Rainfall Simulations

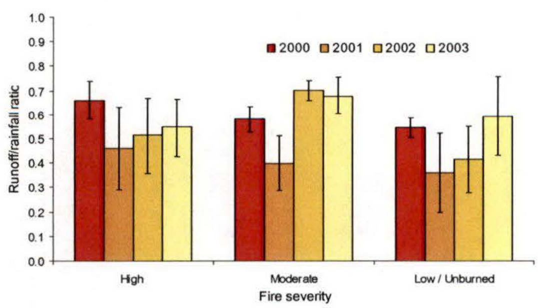
1. Not dependent on natural rain events (or lack thereof);
2. Provides comparable data between sites;
3. More rigorous evaluation of selected factors (e.g., soil type, fire severity, etc.).

Number of Simulations by Severity and Fire

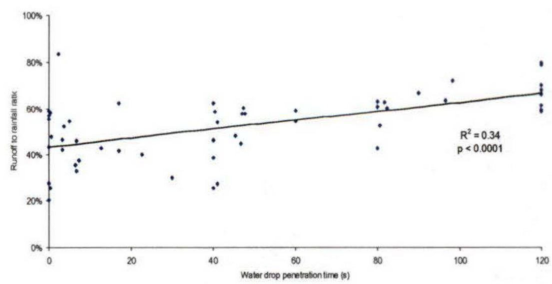
Fire	2000			2001			2002			2003			Totals
	Severity			Severity			Severity			Severity			
	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	High	Mod.	Low/ unb.	
Bobcat	7	5	4	6	4	4	11	3	4	5	2	2	57
L. Flowers *	2	2	2	3	3	3	-	-	-	-	-	-	15
Hourglass	2	0	2	-	-	-	-	-	-	-	-	-	4
Hayman	-	-	-	-	-	-	-	-	-	20	-	-	20
	11	7	8	9	7	7	11	3	4	25	2	2	96

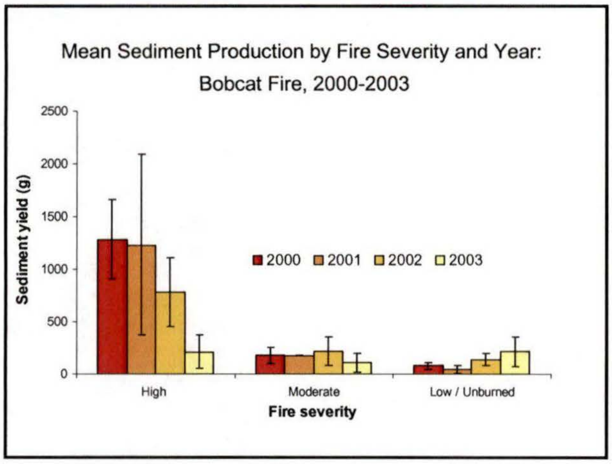
* Prescribed fire

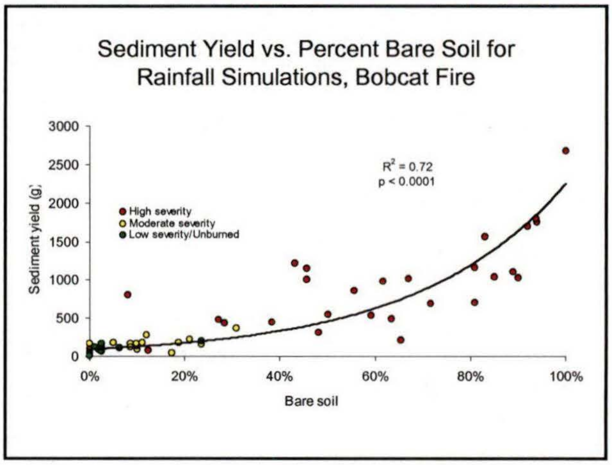
Mean Runoff/Rainfall Ratio by Fire Severity and Year: Bobcat Fire, 2000-2003

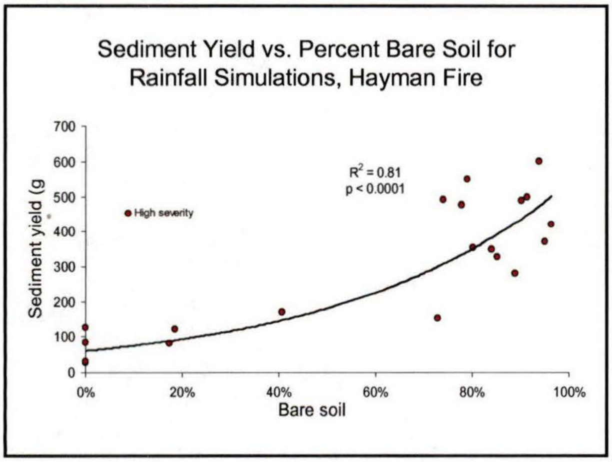


Soil Water Repellency vs. Runoff/Rainfall Ratio: High Severity Sites




Mean Sediment Production by Fire Severity and Year:
Bobcat Fire, 2000-2003
Sediment yield (g)
2500
2000
1500
1000
500
0
2000
2001
2002
2003
High
Moderate
Low / Unburned
Fire severity


Sediment Yield vs. Percent Bare Soil for
Rainfall Simulations, Bobcat Fire
Sediment yield (g)
3000
2500
2000
1500
1000
500
0
High severity
Moderate severity
Low severity/Unburned
$R^2 = 0.72$
$p < 0.0001$
0%
20%
40%
60%
80%
100%
Bare soil

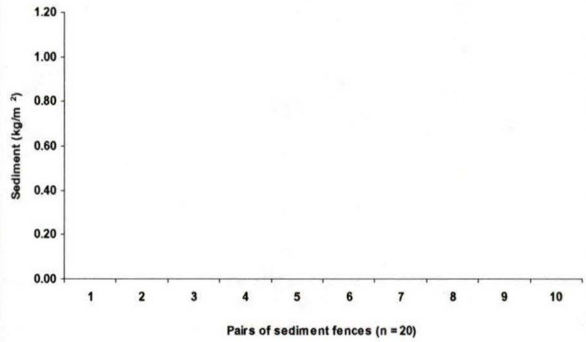

Sediment Yield vs. Percent Bare Soil for
Rainfall Simulations, Hayman Fire
Sediment yield (g
700
600
500
400
300
200
100
0
High severity
$R^2 = 0.81$
$p < 0.0001$
0%
20%
40%
60%
80%
100%
Bare soil


Sediment Production at the
Hillslope Scale
9 7 2002

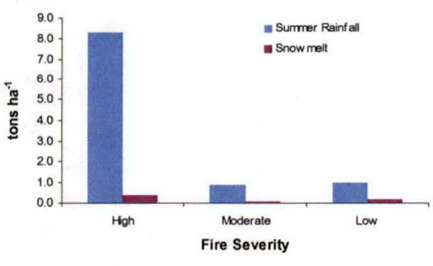
Number of untreated sites by fire and severity

Fire	Date burned	Size of fire (ha)	Primary vegetation type	Sediment fences per severity			
				High	Moderate	Low	Total
Big Elk	Aug-02	1,760	Lodgepole pine	3	2	1	6
Hayman	Jun-02	55,700	Ponderosa pine	31	1	0	32
Schoonover	May-02	1,490	Ponderosa pine	6	0	0	6
Hewlett Gulch	Apr-02	200	Ponderosa pine	3	0	0	3
Bobcat	Jun-00	4,289	Ponderosa pine	13	2	1	16
Dadd Bennett*	Jan-00	200	Ponderosa pine	0	3	2	5
Lower Flowers*	Nov-99	300	Ponderosa pine	4	4	2	10
Crosier Mountain*	Sep-98	1,011	Lodgepole Pine	4	1	0	5
Bear Tracks	Jun-98	196	Subalpine fir	3	0	2	5
Hourglass	Jul-94	516	Lodgepole pine	5	1	1	7
* Prescribed fire			Totals	72	14	9	95

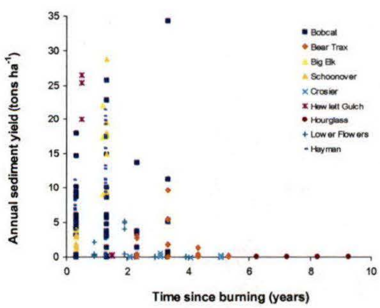
Sediment production: Summer 2001 (before Hayman fire)

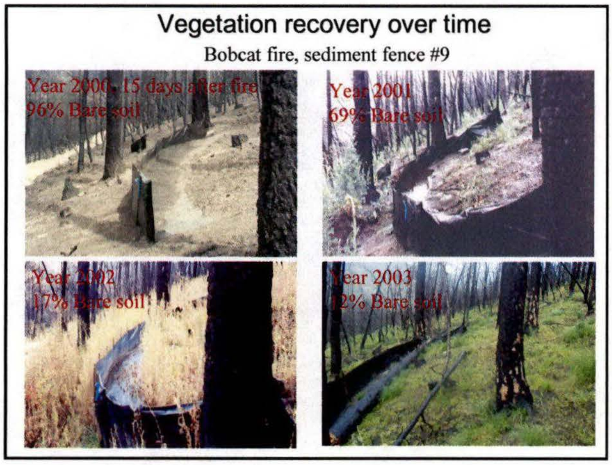


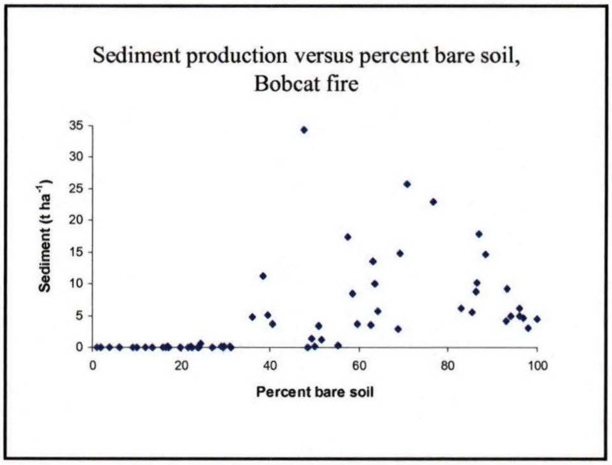
Mean sediment yields by season: first two years after burning, all sites

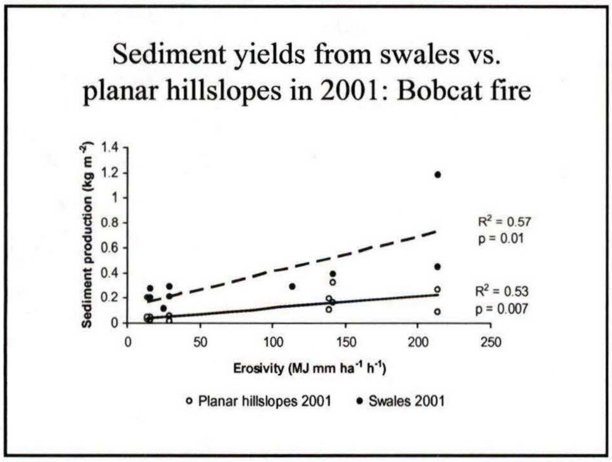


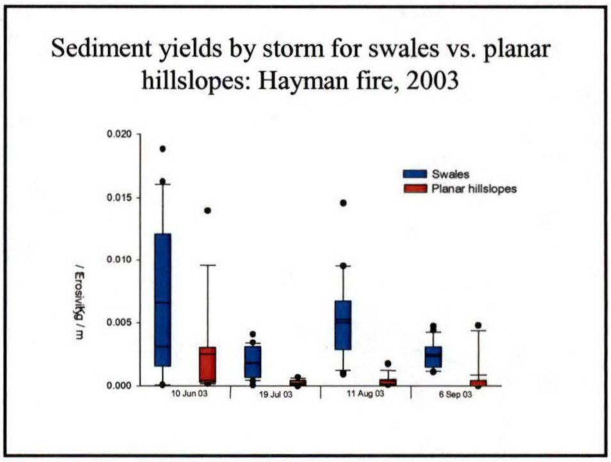
Summer sediment yields vs. time since burning: High-severity sites, all years




Vegetation recovery over time
Bobcat fire, sediment fence #9
Year 2000, 15 days after fire
96% Bare soil
Year 2001
69% Bare soil
Year 2002
17% Bare soil
Year 2003
12% Bare soil

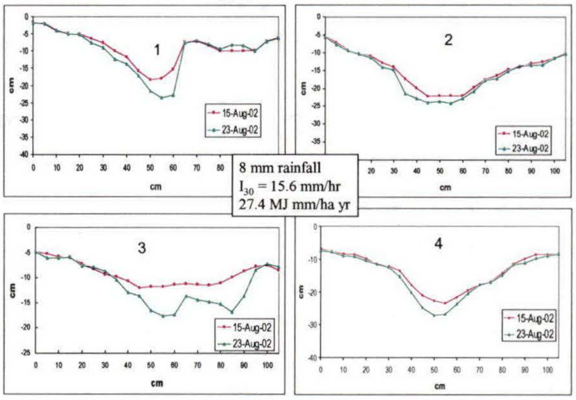

Sediment production versus percent bare soil, Bobcat fire
Sediment (t ha-1)
Percent bare soil
0
20
40
60
80
100
5
10
15
20
25
30
35


Sediment yields from swales vs. planar hillslopes in 2001: Bobcat fire
Sediment production (kg m-2)
Erosivity (MJ mm ha-1 h-1)
R2 = 0.57
p = 0.01
R2 = 0.53
p = 0.007
Planar hillslopes 2001
Swales 2001

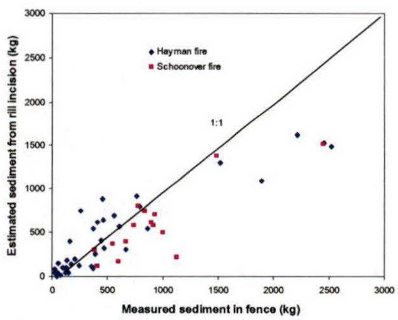

Sediment yields by storm for swales vs. planar hillslopes: Hayman fire, 2003
Swales
Planar hillslopes
0.020
0.015
0.010
0.005
0.000
10 Jun 03
19 Jul 03
11 Aug 03
6 Sep 03

Measuring rill incision, Hayman fire

Cross-section Changes in Swale 4: Storm on 21 August



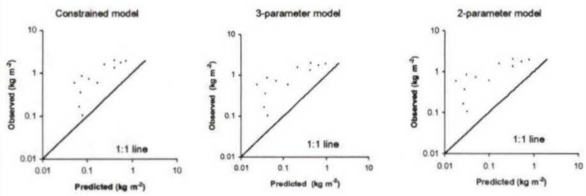
Estimated sediment production from rill incision vs. measured sediment yields

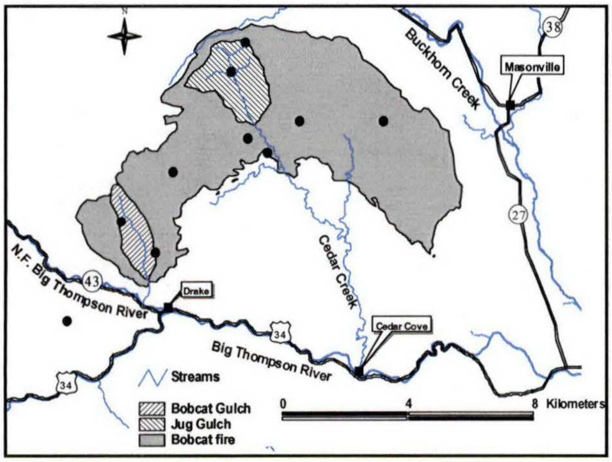


Predicting Hillslope-scale Sediment Yields

Model	Predictive Variables					R^2
Complete	Fire severity	Bare soil	Rainfall erosivity	Soil water repellency	D_{84}	0.77
Constrained	Fire severity	Bare soil	Rainfall erosivity	Time since burning		0.73
3-parameter	Fire severity	Bare soil	Rainfall erosivity			0.70
2-parameter		Bare soil	Rainfall erosivity			0.65

Validation of Hillslope Erosion Models





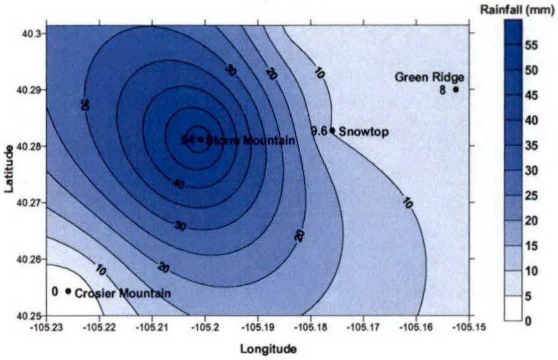
Bobcat Gulch

Jug Gulch

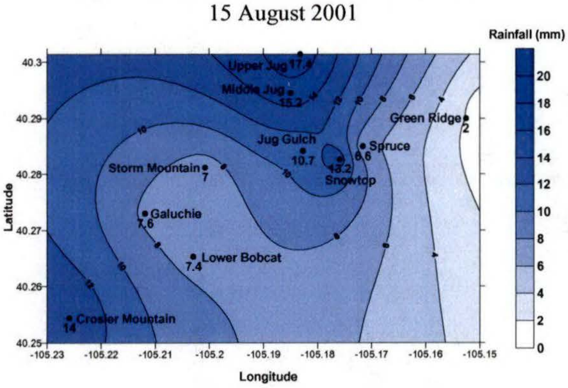
Storm Characteristics and Peak Runoff Rates: Bobcat fire, 2000-2001

Date	Watershed	Depth (mm)	I_{30} (mm hr^{-1})	Peak discharge (L sec^{-1})	Return period
16 Aug 2000	**Bobcat Gulch**	**54**	**42**	**8500**	**25-yr 3-hr**
	Jug Gulch	9.6	14.8	< 18	<1-yr
15 Aug 2001 (#2)	Bobcat Gulch	7.5	14.8	250	<1-yr
	Jug Gulch	**16.3**	**31.6**	**6800**	**2-yr 30-min**
16 Aug 2001	**Bobcat Gulch**	**13.0**	**23.3**	**2300**	**1-yr 30-min**
	Jug Gulch	7.2	13.8	180	<1-yr
3 June 2002	**Bobcat Gulch**	**17.9**	**12.7**	**< 25**	**<1-yr**
	Jug Gulch	14.8	9.6	< 18	<1-yr

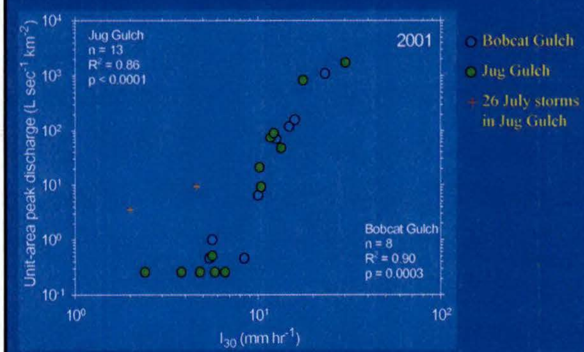
Spatial variability of rain on Bobcat Gulch: 16 August 2000



Spatial variability of rain on Bobcat Gulch: 15 August 2001



Peak discharge vs. 30-minute rainfall intensity (I_{30})



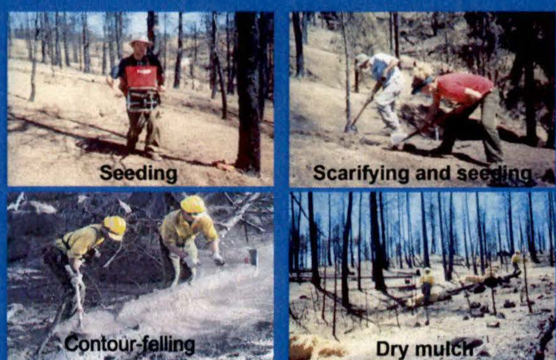
Conclusions: Plot, Hillslope, and Watershed Scales

- Erosion rates increase by several orders of magnitude in sites burned at high severity;
- Erosion rates most strongly correlated with percent cover and rainfall erosivity;
- Rill incision is predominant erosion process rather than sheetwash;
- Minimal recovery until third summer after burning.

Background

- Large amounts of money spent after most major fires (e..g, $25 million after Cerro Grande, $17 million after Hayman);
- Strong political pressure to do something;
- Very few data on effectiveness;
- USFS review stated that effectiveness generally poor (Robichaud et al., 2000).

Typical Emergency Rehabilitation Treatments



Other Techniques

Hydromulch
(aerial and ground-based)

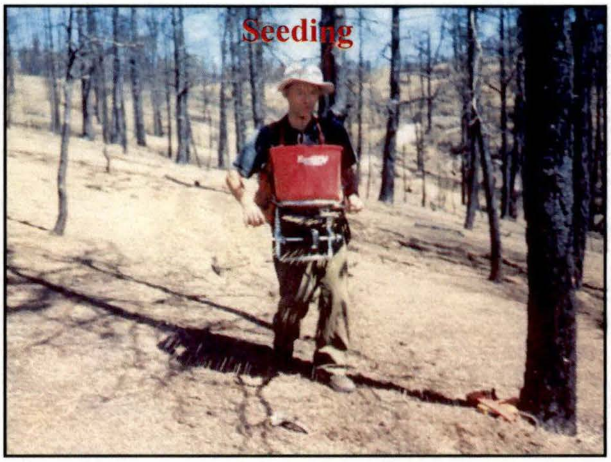
Soil binding agents
(e.g., polyacrylamides)

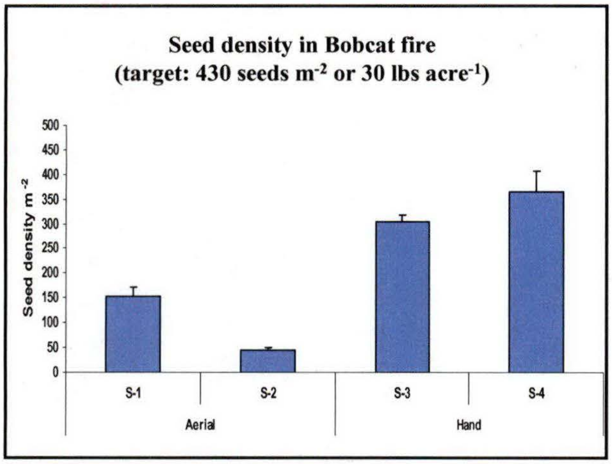
Treatments on Bobcat fire

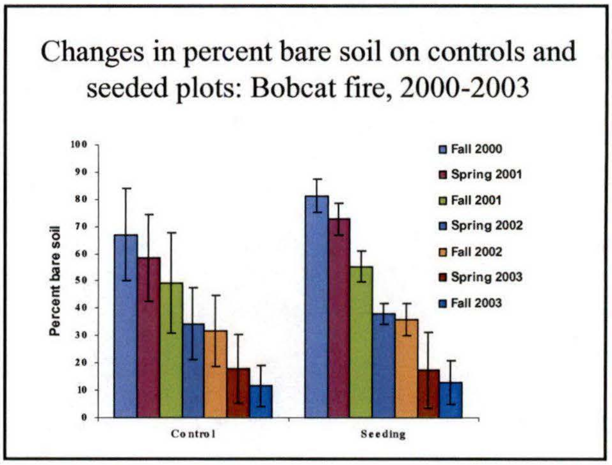
- Mulching: July 2000; Fall 2000;
- Aerial seeding: July 2000
- Contour-felling: July 2000; Fall 2000

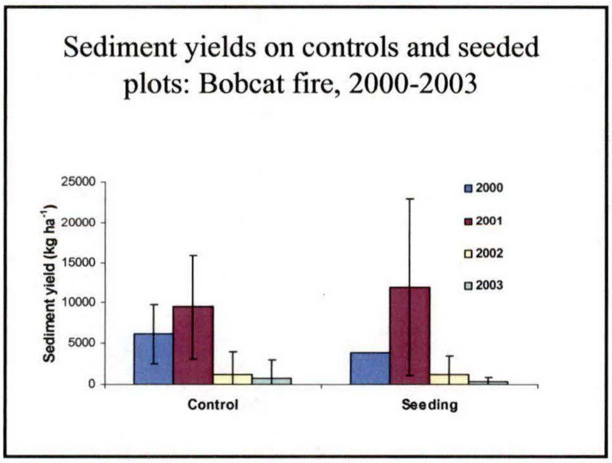
Treatments on Hayman fire: 2002

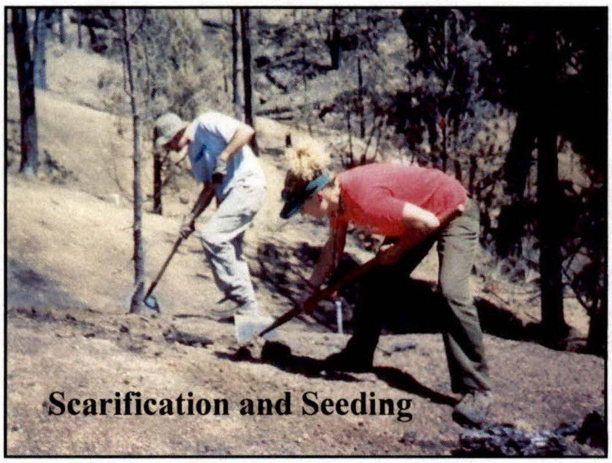
- Scarifying and seeding
- Dry mulching
- Hydromulching
  - Ground based
  - Aerial
- Polyacrylamide



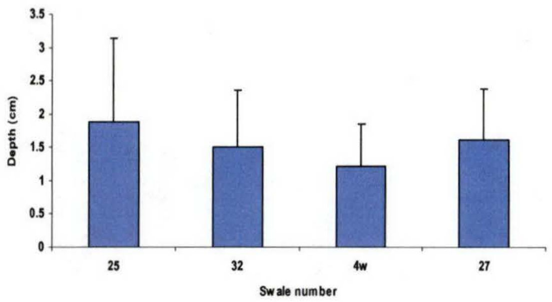

Seed density in Bobcat fire
(target: 430 seeds m-2 or 30 lbs acre-1)
Seed density m -2
S-1
S-2
S-3
S-4
Aerial
Hand


Changes in percent bare soil on controls and seeded plots: Bobcat fire, 2000-2003
Percent bare soil
Fall 2000
Spring 2001
Fall 2001
Spring 2002
Fall 2002
Spring 2003
Fall 2003
Control
Seeding

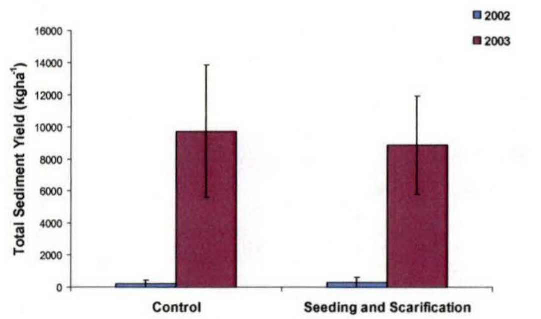

Sediment yields on controls and seeded plots: Bobcat fire, 2000-2003
Sediment yield (kg ha-1)
2000
2001
2002
2003
Control
Seeding


Scarification and Seeding

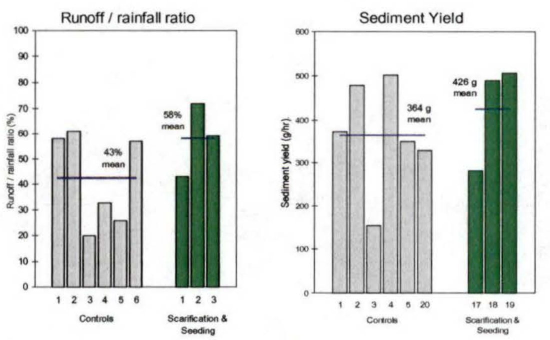
Depth of hand scarification in Hayman fire



Sediment yields for control plots vs. seeding and scarifying: Hayman fire, 2002 and 2003



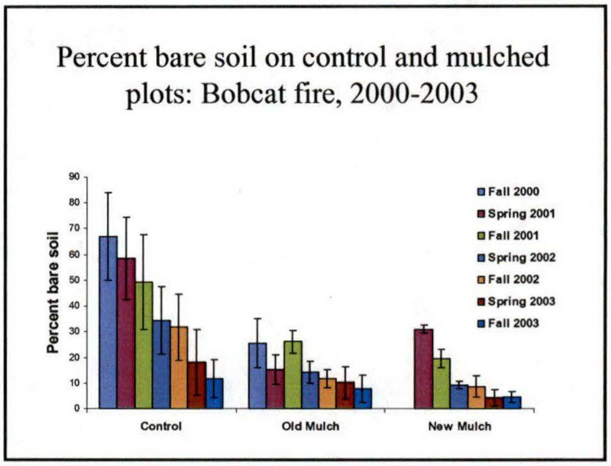
Runoff and Sediment Yields from Simulations on Seeded and Scarified Plots: Hayman Fire, 2003

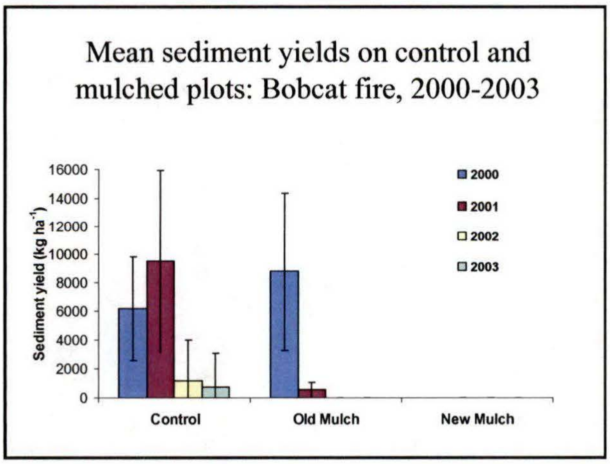


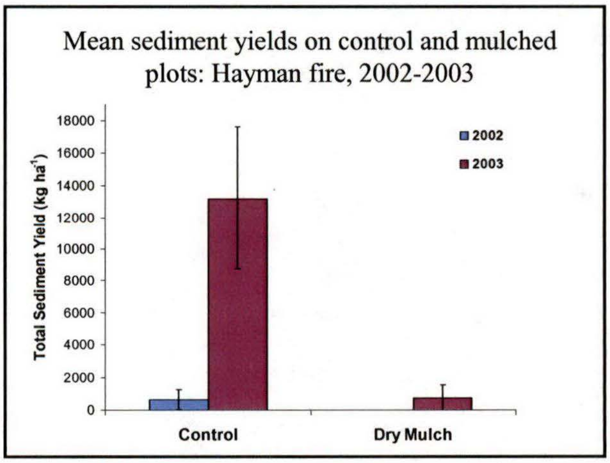
Seeding: Summary

- Uneven seed distribution;
- Depth of scarification probably too shallow to break up water repellent layer;
- No evidence that it increases cover;
- No evidence that it reduces erosion;
- Surface runoff can redistribute seeds;
- Need ideal sequence of storms and lack of natural regeneration for seeding to be effective.

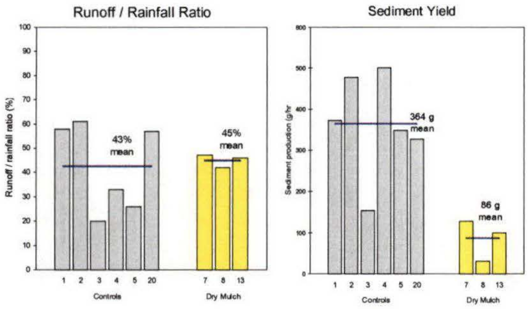

Mulching


Percent bare soil on control and mulched plots: Bobcat fire, 2000-2003
Percent bare soil
Fall 2000
Spring 2001
Fall 2001
Spring 2002
Fall 2002
Spring 2003
Fall 2003
Control
Old Mulch
New Mulch


Mean sediment yields on control and mulched plots: Bobcat fire, 2000-2003
Sediment yield (kg ha-1)
2000
2001
2002
2003
Control
Old Mulch
New Mulch


Mean sediment yields on control and mulched plots: Hayman fire, 2002-2003
Total Sediment Yield (kg ha-1)
2002
2003
Control
Dry Mulch

Runoff and Sediment Yields from Rainfall Simulations on Control and Mulched Plots: Hayman Fire, 2003



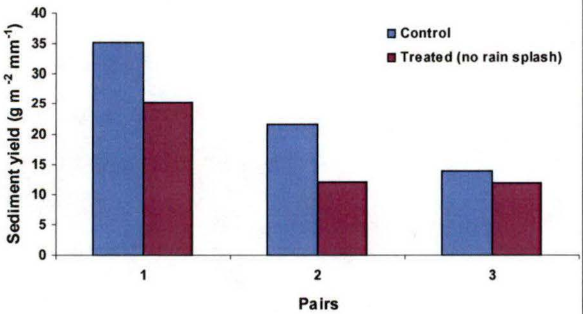
Why is percent cover so important, and mulching so effective?

- Provides immediate cover to reduce rainsplash and overland flow velocities;
- May reduce soil water repellency by increasing soil moisture;
- May improve germination;
- May reduce rill erosion.

→ Effectiveness probably decreases with increasing storm size;

→ Aerial application may provide reasonable cover.

Erosion rates with and without rainsplash at high-severity sites: Bobcat fire



Conclusions

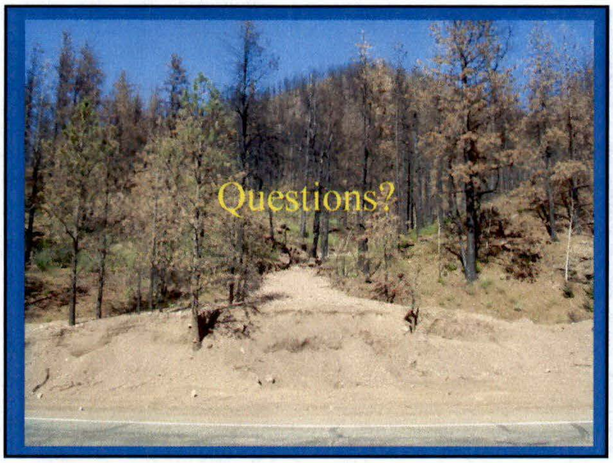
- Wildfires in the Colorado Front Range are strongly correlated with drought conditions;
- Wild and prescribed fires generate a strong water repellent layer, but this is shallow and short-lived;
- Runoff and erosion rates after wildfires can be several orders of magnitude greater than under unburned conditions. Rainfall intensities of 10 mm hr^{-1} can induce overland flow;
- Post-fire erosion due to summer rain storms rather than snowmelt;

Conclusions (2)

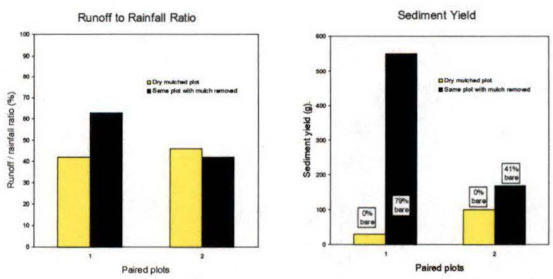
- Rilling appears to be the dominant erosion process at the hillslope and small catchment scale;
- Erosion rates are highly dependent on rainfall intensity and percent cover;
- Erosion rates begin to decline when percent bare soil is less than about 60%, and approach background levels when percent bare soil is less than 30-35%;
- Erosion rates do not decline until the third summer after burning;

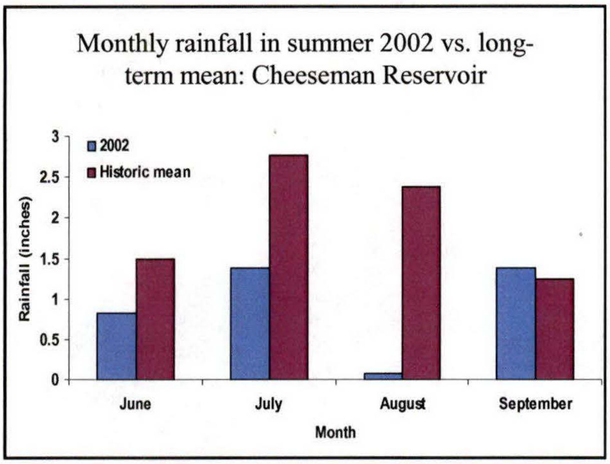
Conclusions (3)

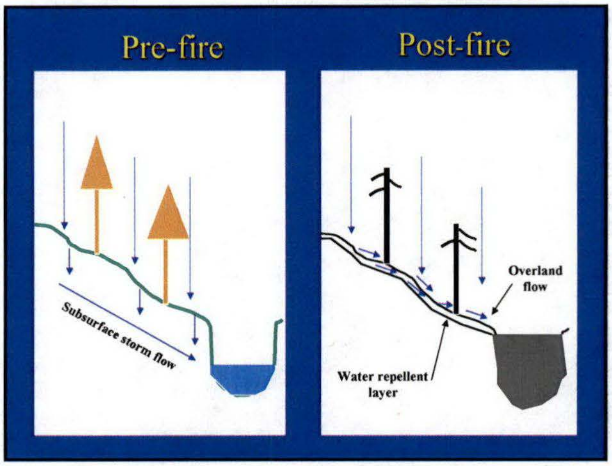
- Mulching is the most effective treatment because it provides immediate cover. Seeding does not significantly increase percent cover or reduce erosion rates;
- Contour felling can store the sediment from an average year, but must be installed correctly;
- Polyacrylamides do not appear to reduce erosion;
- Ground cover can increase soil moisture and seed germination, reduce rainsplash and soil sealing, and slow overland flow. Additional studies are needed to evaluate the relative importance of each of these processes.

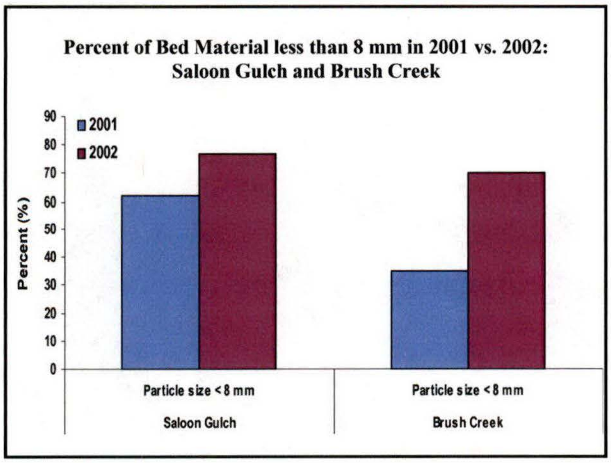


Two Pairs of Mulched / Mulch-Removed Rainfall Simulations, Hayman Fire









Burn Severity Classes

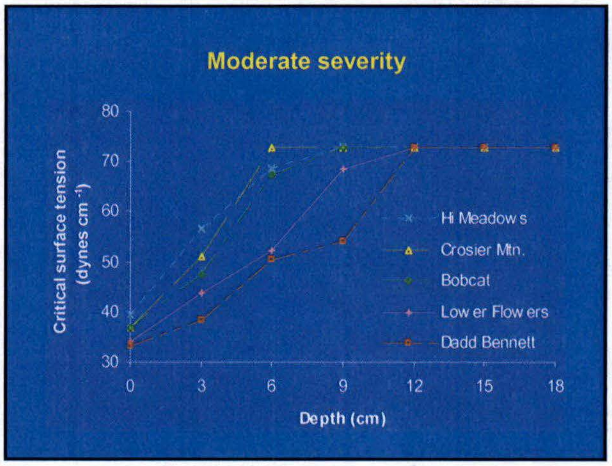
- High severity: DEFINE;
- Moderate severity:;
- Low severity:

- Results often stratified by burn severity class because this greatly affects the magnitude of change in runoff and erosion.

Results

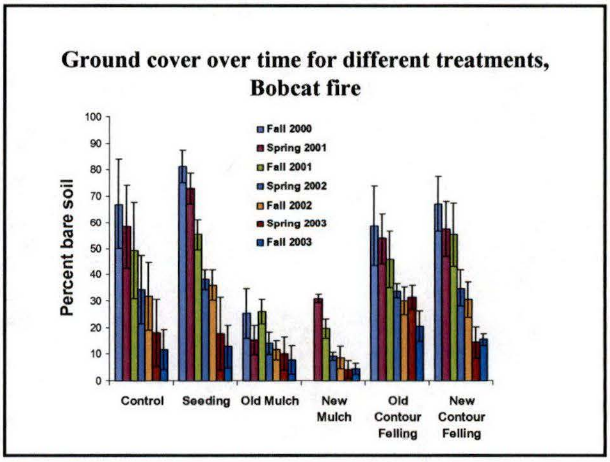
- CST test less variable within and between sites than WDPT;
- Generates a single number for each depth;
- CST faster and easier to determine in the field;
- Value is a quantitative measure of the strength of soil water repellency.

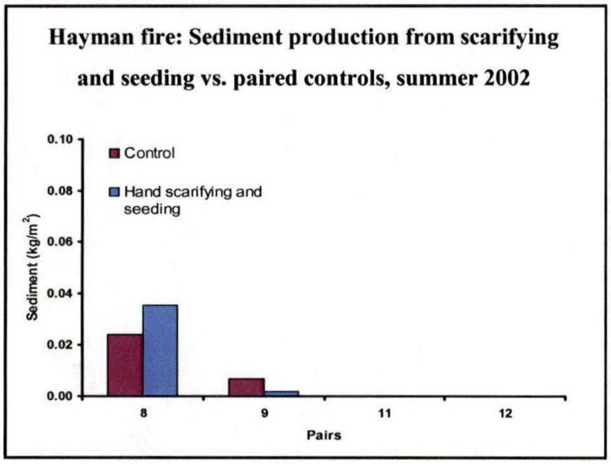
  – (Huffman, MacDonald, and Stednick, *Hydro. Proc.*, 2001)

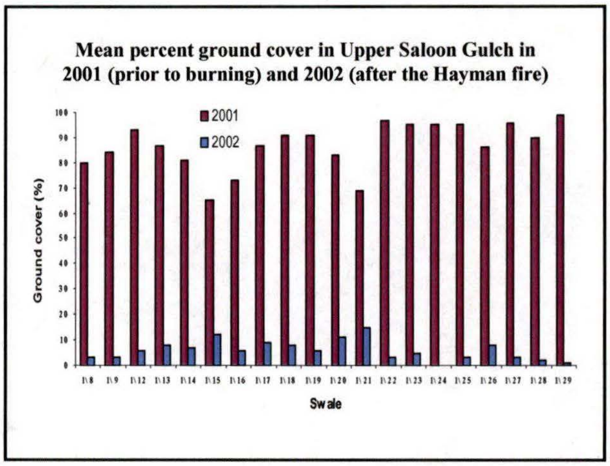


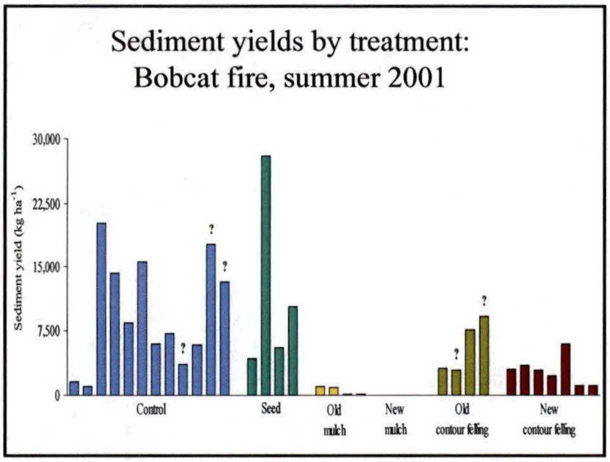
Storm Characteristics and Suspended Sediment: Bobcat fire

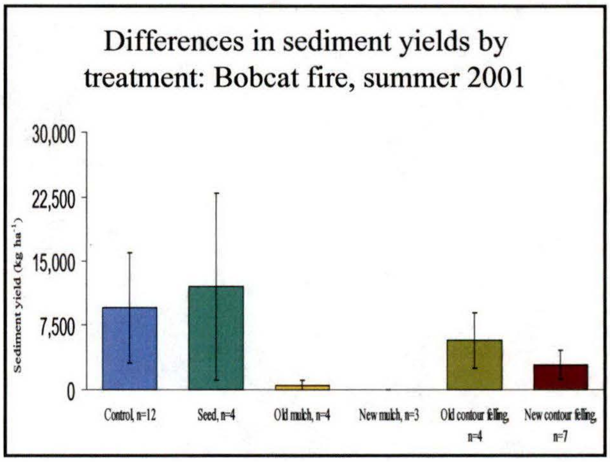
Date	Watershed	Depth (mm)	I_{30} (mm hr^{-1})	Sediment yield (kg ha^{-1})	Return period
8 July 2001	**Bobcat Gulch**	**6.3**	**12.6**	0.3	<1-yr
	Jug Gulch	4.5	9.0	**1.2**	<1-yr
15 Aug 2001 (#2)	Bobcat Gulch	7.5	14.8	1.4	<1-yr
	Jug Gulch	**16.3**	**31.6**	**950**	**2-yr 30-min**
16 Aug 2001	**Bobcat Gulch**	**13.0**	**23.3**	**370**	**1-yr 30-min**
	Jug Gulch	7.2	13.8	25	<1-yr

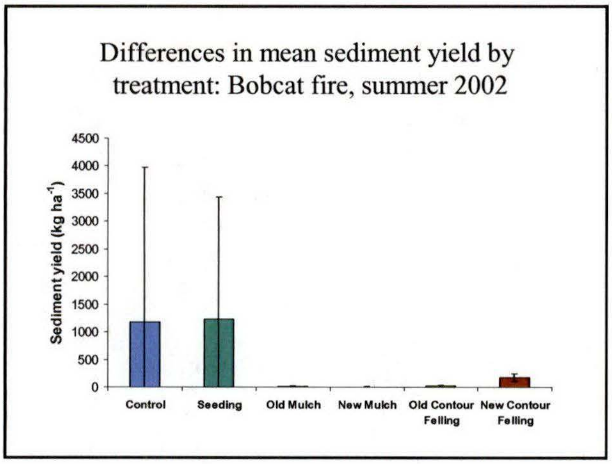


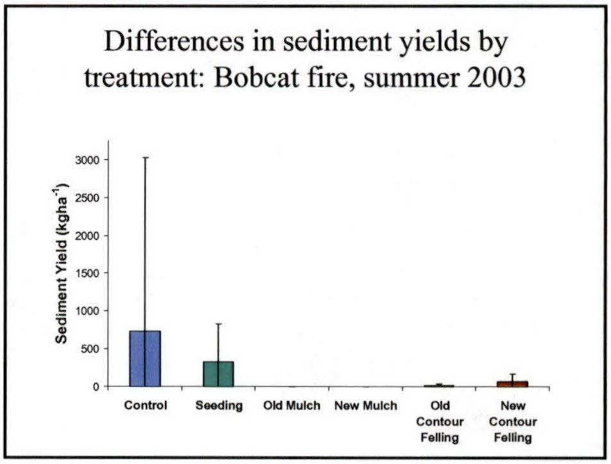

Hayman fire: Sediment production from scarifying and seeding vs. paired controls, summer 2002
Control
Hand scarifying and seeding
Sediment (kg/m^2)
0.10
0.08
0.06
0.04
0.02
0.00
8
9
11
12
Pairs

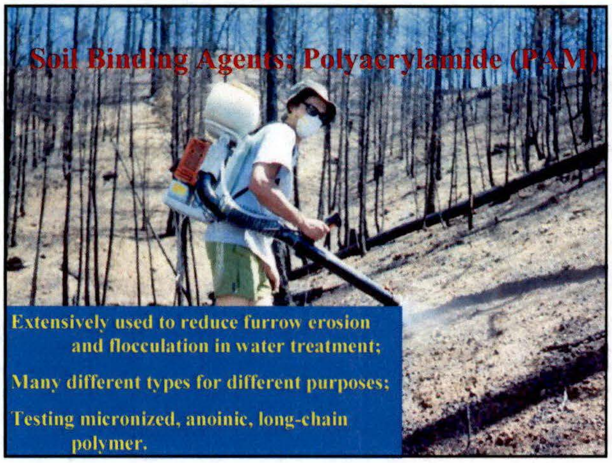

Mean percent ground cover in Upper Saloon Gulch in 2001 (prior to burning) and 2002 (after the Hayman fire)
2001
2002
Ground cover (%)
Swale

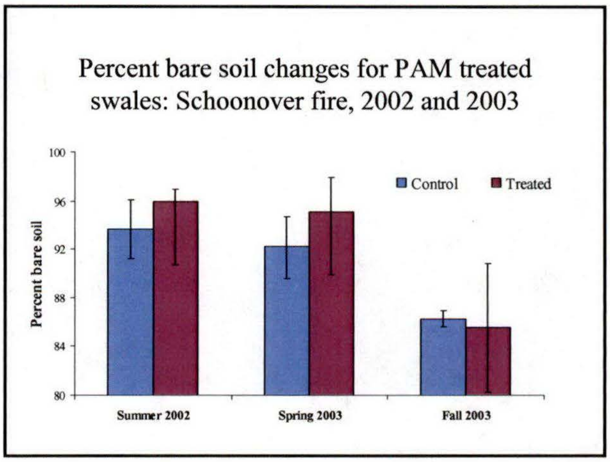

Sediment yields by treatment: Bobcat fire, summer 2001
Sediment yield (kg ha^{-1})
30,000
22,500
15,000
7,500
0
Control
Seed
Old mulch
New mulch
Old contour felling
New contour felling


Differences in sediment yields by treatment: Bobcat fire, summer 2001
Sediment yield (kg ha^{-1})
30,000
22,500
15,000
7,500
0
Control, n=12
Seed, n=4
Old mulch, n=4
New mulch, n=3
Old contour felling, n=4
New contour felling, n=7

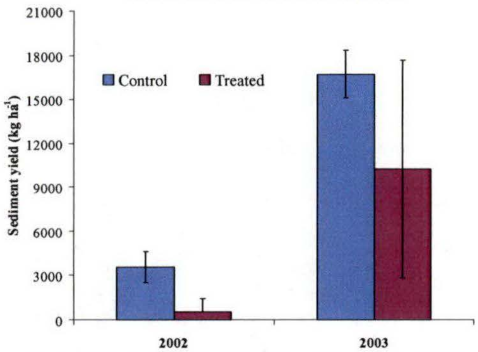

Differences in mean sediment yield by treatment: Bobcat fire, summer 2002
Sediment yield (kg ha-1)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Control
Seeding
Old Mulch
New Mulch
Old Contour Felling
New Contour Felling


Differences in sediment yields by treatment: Bobcat fire, summer 2003
Sediment Yield (kgha-1)
3000
2500
2000
1500
1000
500
0
Control
Seeding
Old Mulch
New Mulch
Old Contour Felling
New Contour Felling

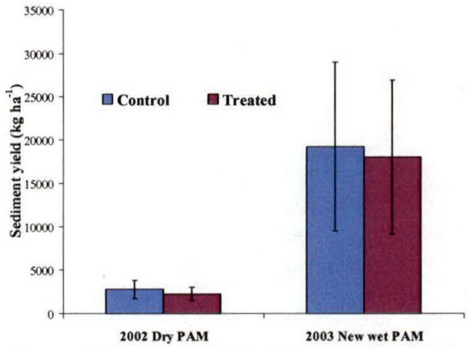

Soil Binding Agents: Polyacrylamide (PAM)
Extensively used to reduce furrow erosion and flocculation in water treatment;
Many different types for different purposes;
Testing micronized, anoinic, long-chain polymer.


Percent bare soil changes for PAM treated swales: Schoonover fire, 2002 and 2003
Percent bare soil
100
96
92
88
84
80
Control
Treated
Summer 2002
Spring 2003
Fall 2003

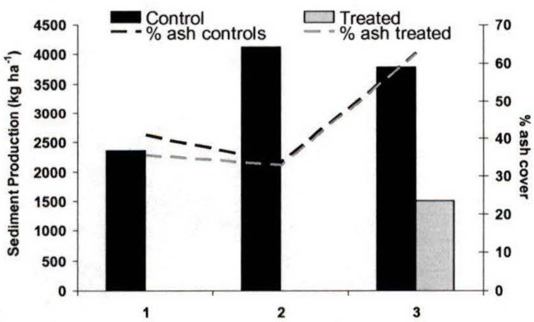
Sediment yields for wet PAM treatment 2002-2003



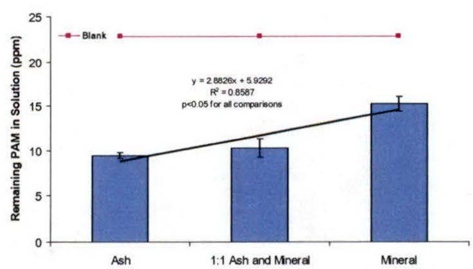
Sediment yields for dry and new wet PAM treatments 2002-2003



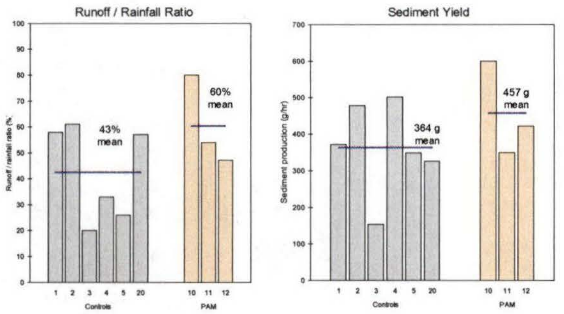
Percent ash and sediment yields for wet PAM treated sites



PAM attenuation in ash and mineral soil samples

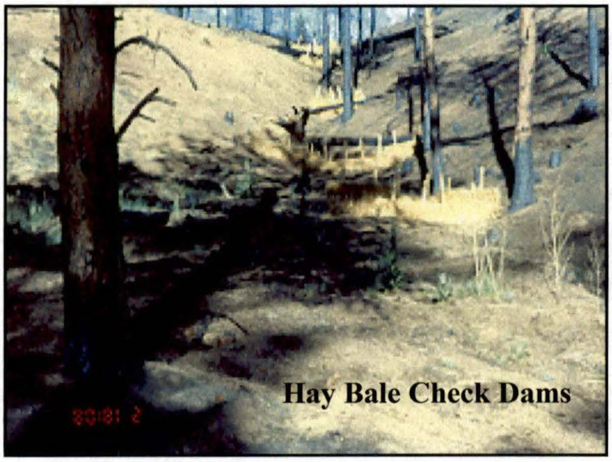


PAM Treatment
Rainfall Simulations, Hayman Fire



Effectiveness of PAM: Summary

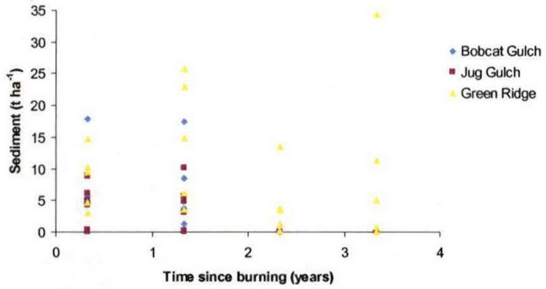
- Potential chemical interaction with ash;
- Wet formulation probably more effective than dry;
- May be most effective when mixed with hydromulch;
- Effectiveness complicated by:
  - Different formulations;
  - Different means of applications;
  - Different rates of application;
  - Effects of soil texture and ash.



Hay Bale Check Dams

- Extensively used on construction sites;
- Generally more difficult to effectively treat downstream areas than source areas;
- No quantitative data being collected, but could estimate sediment storage capacity and compare to erosion rates on untreated sites;
- Need explicit study to evaluate effectiveness.

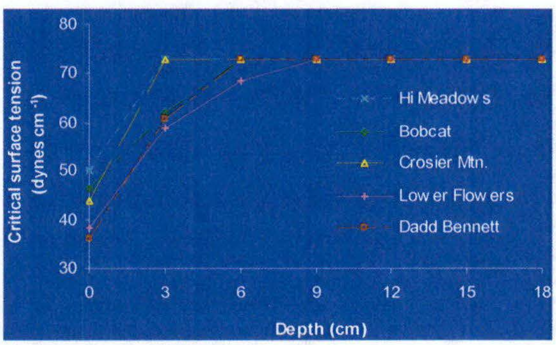
Summer sediment yields from high severity sites vs. time since burning: Bobcat fire

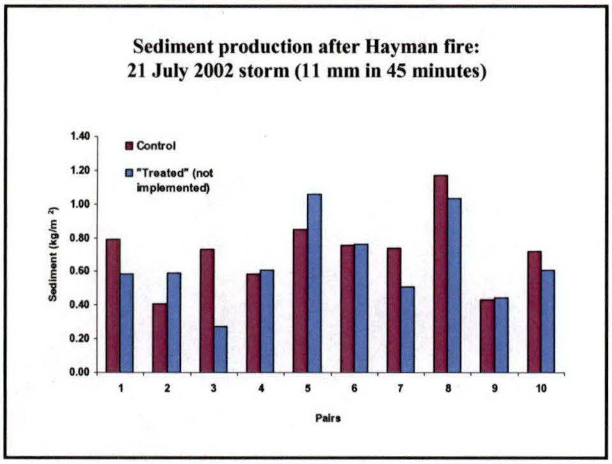


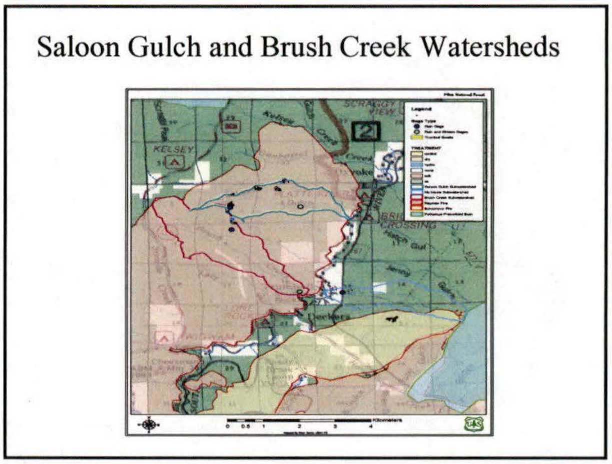
Additional Data

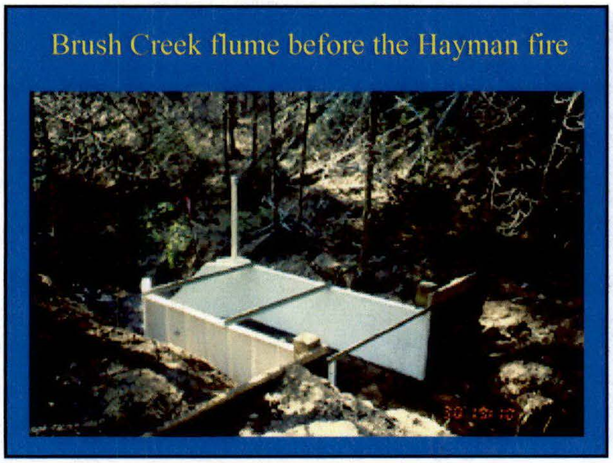
- Measuring key site factors:
  - Precipitation amounts and intensity;
  - Soil texture;
  - Slope;
  - Contributing area;
  - Soil water repellency;
  - Percent ground cover.

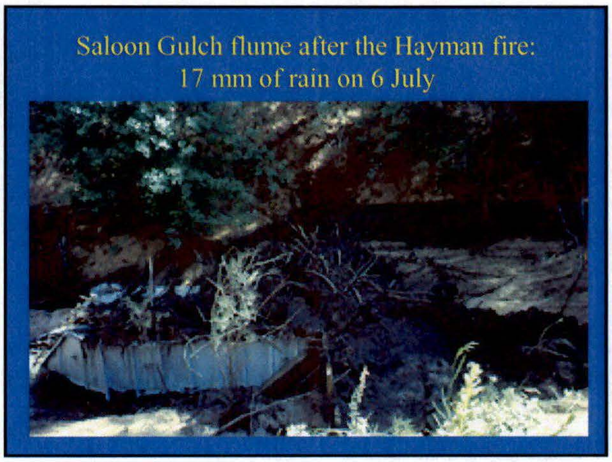
Low severity sites

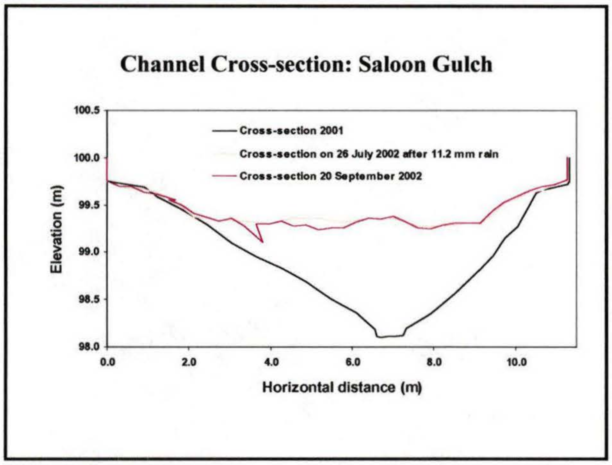


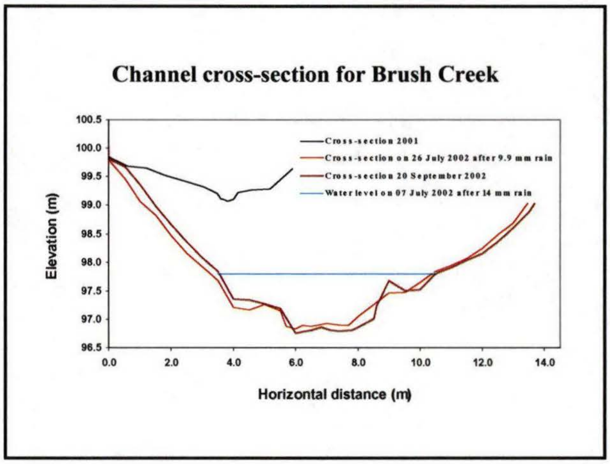

Sediment production after Hayman fire:
21 July 2002 storm (11 mm in 45 minutes)
Control
"Treated" (not implemented)
Sediment (kg/m²)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Pairs

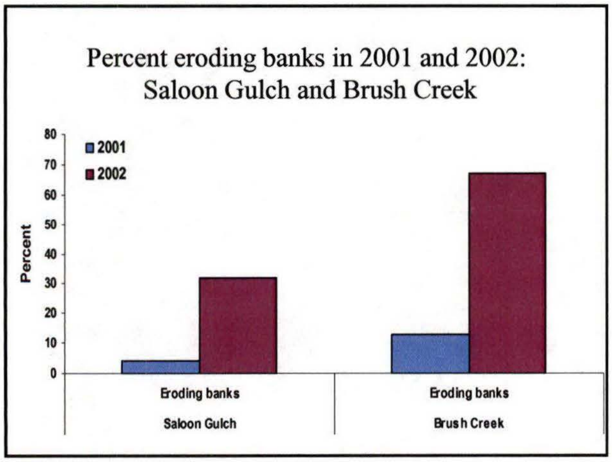

Saloon Gulch and Brush Creek Watersheds
KELSEY

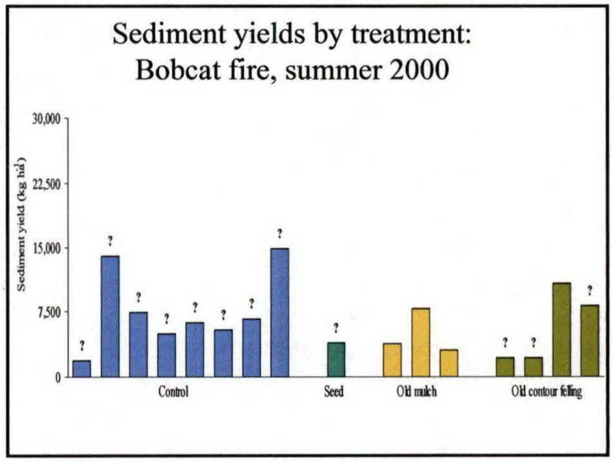

Brush Creek flume before the Hayman fire


Saloon Gulch flume after the Hayman fire:
17 mm of rain on 6 July

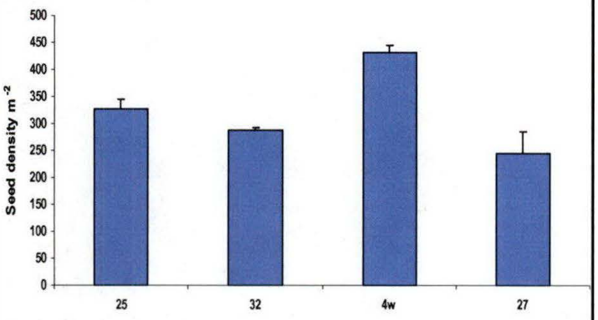

Channel Cross-section: Saloon Gulch
Cross-section 2001
Cross-section on 26 July 2002 after 11.2 mm rain
Cross-section 20 September 2002
Elevation (m)
100.5
100.0
99.5
99.0
98.5
98.0
0.0
2.0
4.0
6.0
8.0
10.0
Horizontal distance (m)


Channel cross-section for Brush Creek
Cross-section 2001
Cross-section on 26 July 2002 after 9.9 mm rain
Cross-section 20 September 2002
Water level on 07 July 2002 after 14 mm rain
Elevation (m)
100.5
100.0
99.5
99.0
98.5
98.0
97.5
97.0
96.5
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Horizontal distance (m)

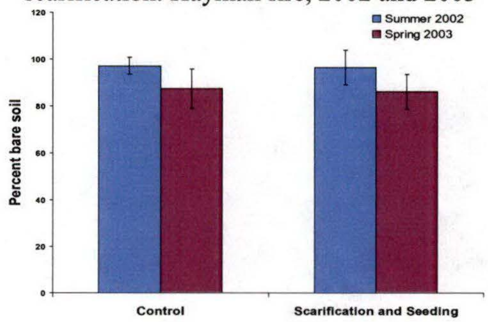

Percent eroding banks in 2001 and 2002:
Saloon Gulch and Brush Creek
2001
2002
Percent
80
70
60
50
40
30
20
10
0
Eroding banks
Saloon Gulch
Eroding banks
Brush Creek


Sediment yields by treatment:
Bobcat fire, summer 2000
30,000
22,500
15,000
7,500
0
Control
Seed
Old mulch
Old contour felling

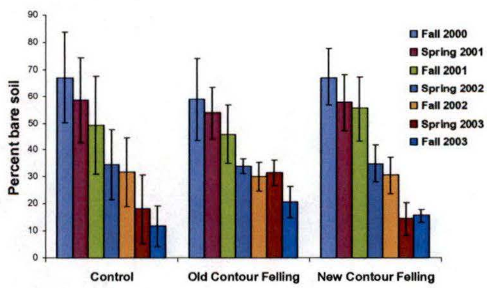
Seed density in Hayman fire
(target: 280-380 seeds m^{-2})



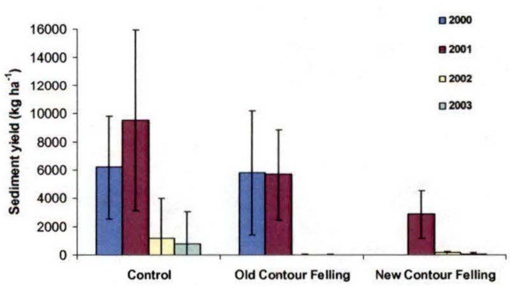
Percent bare soil changes for seeding and scarification: Hayman fire, 2002 and 2003



Changes in percent bare soil on contour-felled plots: Bobcat fire, 2000-2003



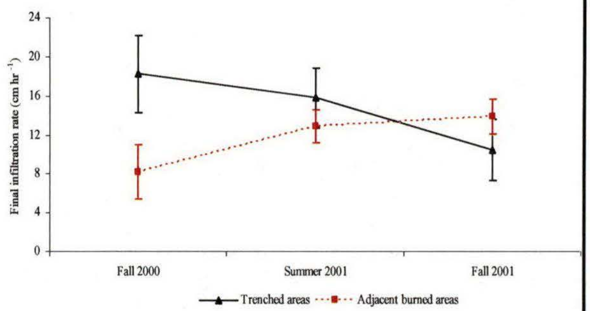
Sediment yields on contour-felled plots: Bobcat fire, 2000-2003



Contour-felling Effectiveness

Site	Mean value for each site			Total failures (percent)	Site storage capacity (m^3 ha^{-1})
	Log density (m log ha^{-1})	Log length (m)	Log diameter (m)		
Bobcat	161	5.6	0.25	27	6.8
Galuchie	147	4.4	0.27	27	7.2
Spruce	538	6.6	0.25	10	18
Eldorado B-1	939	3.2	0.18	27	12
Eldorado G-1	855	2.9	0.19	23	29
Hi Meadows HST-3	776	5.8	0.20	40	32
Hi Meadows HST-2	1,310	6.2	0.23	70	9.0
Overall mean	**676**	**5.0**	**0.23**	**32**	**16**

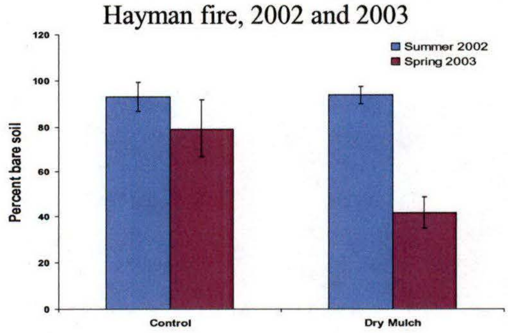
Infiltration rates over time, Bobcat fire

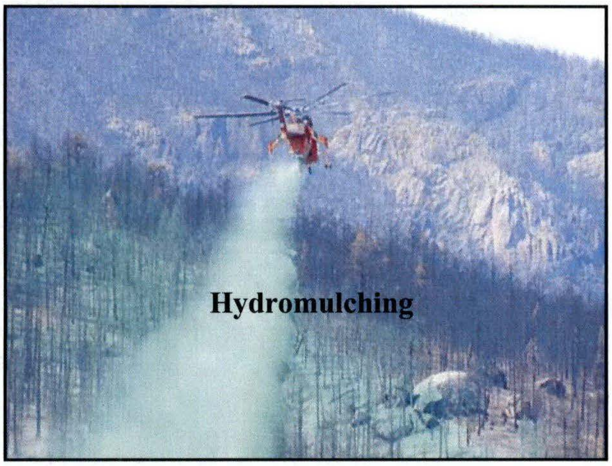


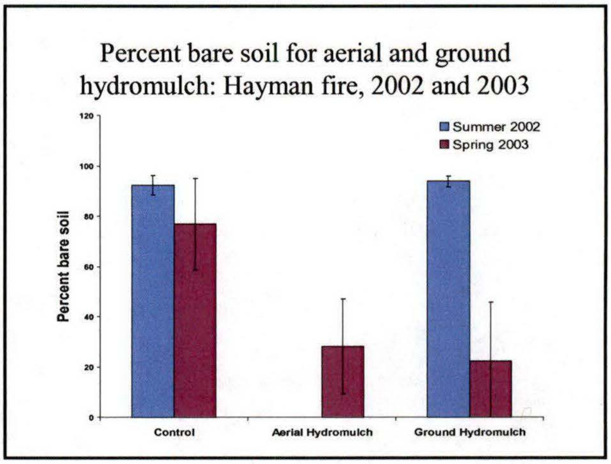
Contour-felling: Summary

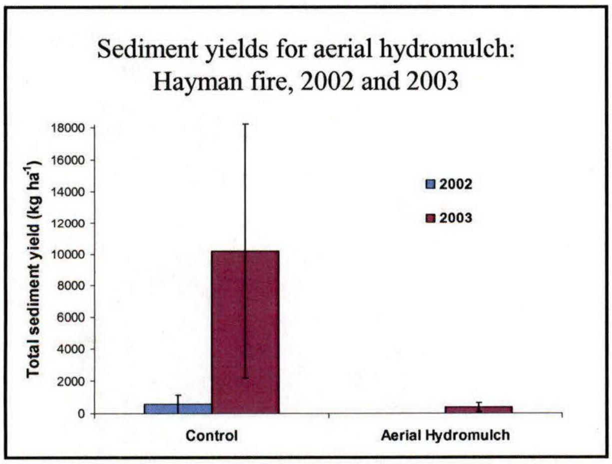
- Increase in infiltration capacity short-lived and limited in area;
- Potential to capture only 2-3 mm of runoff;
- Wide range of potential sediment storage values varying with:
  - Size of contour-felled logs;
  - Density of contour-felled logs;
  - Quality of installation;
- Could potentially capture most of sediment from an average summer;
- Poor installation can increase rill erosion;
- Not very cost-effective.

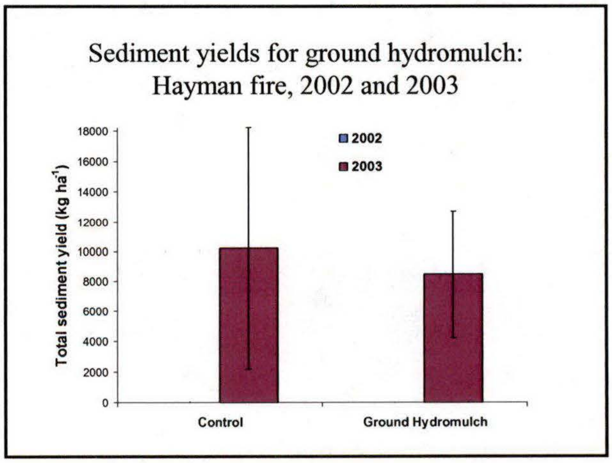
Percent bare soil changes for dry mulch: Hayman fire, 2002 and 2003

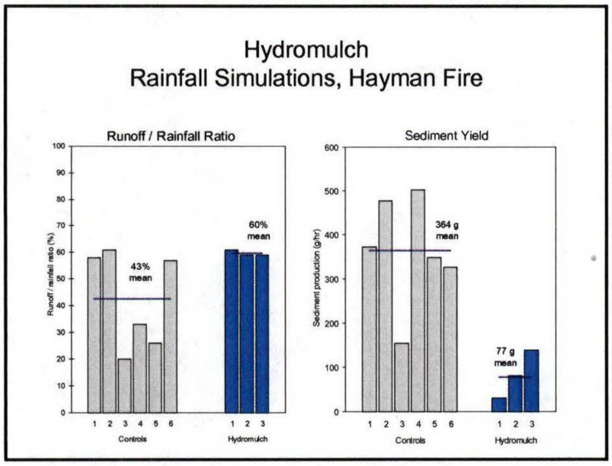



Hydromulching


Percent bare soil for aerial and ground hydromulch: Hayman fire, 2002 and 2003
Summer 2002
Spring 2003
Percent bare soil
0
20
40
60
80
100
120
Control
Aerial Hydromulch
Ground Hydromulch


Sediment yields for aerial hydromulch: Hayman fire, 2002 and 2003
2002
2003
Total sediment yield (kg ha-1)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Control
Aerial Hydromulch


Sediment yields for ground hydromulch: Hayman fire, 2002 and 2003
2002
2003
Total sediment yield (kg ha-1)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Control
Ground Hydromulch



Hydromulch
Rainfall Simulations, Hayman Fire
Runoff / Rainfall Ratio
Runoff / rainfall ratio (%)
43% mean
60% mean
Controls
Hydromulch
Sediment Yield
Sediment production (g/hr)
364 g mean
77 g mean
Controls
Hydromulch